

*Physics**Physics Research Publications*

---

*Purdue University**Year 2010*

---

# Measurement of W-Boson Polarization in Top-Quark Decay in $p(\bar{p})$ Collisions at $\sqrt{s}=1.96$ TeV

T. Aaltonen, J. Adelman, B. A. Gonzalez, S. Amerio, D. Amidei, A. Anastassov, A. Annovi, J. Antos, G. Apollinari, J. Appel, A. Apresyan, T. Arikawa, A. Artikov, J. Asaadi, W. Ashmanskas, A. Attal, A. Aurisano, F. Azfar, W. Badgett, A. Barbaro-Galtieri, V. E. Barnes, B. A. Barnett, P. Barria, P. Bartos, G. Bauer, P. H. Beauchemin, F. Bedeschi, D. Beecher, S. Behari, G. Bellettini, J. Bellinger, D. Benjamin, A. Beretvas, A. Bhatti, M. Binkley, D. Bisello, I. Bizjak, R. E. Blair, C. Blocker, B. Blumenfeld, A. Bocci, A. Bodek, V. Boisvert, D. Bortoletto, J. Boudreau, A. Boveia, B. Brau, A. Bridgeman, L. Brigliadori, C. Bromberg, E. Brubaker, J. Budagov, H. S. Budd, S. Budd, K. Burkett, G. Busetto, P. Bussey, A. Buzatu, K. L. Byrum, S. Cabrera, C. Calancha, S. Camarda, M. Campanelli, M. Campbell, F. Canelli, A. Canepa, B. Carls, D. Carlsmith, R. Carosi, S. Carrillo, S. Carron, B. Casal, M. Casarsa, A. Castro, P. Catastini, D. Cauz, V. Cavaliere, M. Cavalli-Sforza, A. Cerri, L. Cerrito, S. H. Chang, Y. C. Chen, M. Chertok, G. Chiarelli, G. Chlachidze, F. Chlebana, K. Cho, D. Chokheli, J. P. Chou, K. Chung, W. H. Chung, Y. S. Chung, T. Chwalek, C. I. Ciobanu, M. A. Ciocci, A. Clark, D. Clark, G. Compostella, M. E. Convery, J. Conway, M. Corbo, M. Cordelli, C. A. Cox, D. J. Cox, F. Crescioli, C. C. Almenar, J. Cuevas, R. Culbertson, J. C. Cully, D. Dagenhart, N. d'Asenzo, M. Datta, T. Davies, P. de Barbaro, S. De Cecco, A. Deisher, G. De Lorenzo, M. Dell'Orso, C. Deluca, L. Demortier, J. Deng, M. Deninno, M. d'Errico, A. Di Canto, B. Di Ruzza, J. R. Dittmann, M. D'Onofrio, S. Donati, P. Dong, T. Dorigo, S. Dube, K. Ebina, A. Elagin, R. Erbacher, D. Errede, S. Errede, N. Ershaidat, R. Eusebi, H. C. Fang, S. Farrington, W. T. Fedorko, R. G. Feild, M. Feindt, J. P. Fernandez, C. Ferrazza, R. Field, G. Flanagan, R. Forrest, M. J. Frank, M. Franklin, J. C. Freeman, I. Furic, M. Gallinaro, J. Galyardt, F. Garbersson, J. E. Garcia, A. F. Garfinkel, P. Garosi, H. Gerberich, D. Gerdes, A. Gessler, S. Giagu, V. Giakoumopoulou, P. Gianetti, K. Gibson, J. L. Gimmell, C. M. Ginsburg, N. Giokaris, M. Giordani, P. Giromini, M. Giunta, G. Giurgiu, V. Glagolev, D. Glenzinski, M. Gold, N.

Goldschmidt, A. Golossanov, G. Gomez, G. Gomez-Ceballos, M. Goncharov, O. Gonzalez, I. Gorelov, A. T. Goshaw, K. Goulianos, A. Gresele, S. Grinstein, C. Grosso-Pilcher, R. C. Group, U. Grundler, J. G. da Costa, Z. Gunay-Unalan, C. Haber, S. R. Hahn, E. Halkiadakis, B. Y. Han, J. Y. Han, F. Happacher, K. Hara, D. Hare, M. Hare, R. F. Harr, M. Hartz, K. Hatakeyama, C. Hays, M. Heck, J. Heinrich, M. Herndon, J. Heuser, S. Hewamanage, D. Hidas, C. S. Hill, D. Hirschbuehl, A. Hocker, S. Hou, M. Houlden, S. C. Hsu, R. E. Hughes, M. Hurwitz, U. Husemann, M. Hussein, J. Huston, J. Incandela, G. Introzzi, M. Iori, A. Ivanov, E. James, D. Jang, B. Jayatilaka, E. J. Jeon, M. K. Jha, S. Jindariani, W. Johnson, M. Jones, K. K. Joo, S. Y. Jun, J. E. Jung, T. R. Junk, T. Kamon, D. Kar, P. E. Karchin, Y. Kato, R. Kephart, W. Ketchum, J. Keung, V. Khotilovich, B. Kilminster, D. H. Kim, H. S. Kim, H. W. Kim, J. E. Kim, M. J. Kim, S. B. Kim, S. H. Kim, Y. K. Kim, N. Kimura, L. Kirsch, S. Klimenko, K. Kondo, D. J. Kong, J. Konigsberg, A. Korytov, A. V. Kotwal, M. Krepes, J. Kroll, D. Krop, N. Krumnack, M. Kruse, V. Krutelyov, T. Kuhr, N. P. Kulkarni, M. Kurata, S. Kwang, A. T. Laasanen, S. Lami, S. Lammel, M. Lancaster, R. L. Lander, K. Lannon, A. Lath, G. Latino, I. Lazzizzera, T. LeCompte, E. Lee, H. S. Lee, J. S. Lee, S. W. Lee, S. Leone, J. D. Lewis, C. J. Lin, J. Linacre, M. Lindgren, E. Lipeles, A. Lister, D. O. Litvintsev, C. Liu, T. Liu, N. S. Lockyer, A. Loginov, L. Lovas, D. Lucchesi, J. Lueck, P. Lujan, P. Lukens, G. Lungu, J. Lys, R. Lysak, D. MacQueen, R. Madrak, K. Maeshima, K. Makhouf, P. Maksimovic, S. Malde, S. Malik, G. Manca, A. Manousakakis-Katsikakis, F. Margaroli, C. Marino, C. P. Marino, A. Martin, V. Martin, M. Martinez, R. Martinez-Ballarín, P. Mastrandrea, M. Mathis, M. E. Mattson, P. Mazzanti, K. S. McFarland, P. McIntyre, R. McNulty, A. Mehta, P. Mehtala, A. Menzione, C. Mesropian, T. Miao, D. Mietlicki, N. Miladinovic, R. Miller, C. Mills, M. Milnik, A. Mitra, G. Mitselmakher, H. Miyake, S. Moed, N. Moggi, M. N. Mondragon, C. S. Moon, R. Moore, M. J. Morello, J. Morlock, P. M. Fernandez, J. Mulmenstadt, A. Mukherjee, T. Muller, P. Murat, M. Mussini, J. Nachtman, Y. Nagai, J. Naganoma, K. Nakamura, I. Nakano, A. Napier, J. Nett, C. Neu, M. S. Neubauer, S. Neubauer, J. Nielsen, L. Nodulman, M. Norman, O. Norniella, E. Nurse, L. Oakes, S. H. Oh, Y. D. Oh, I. Oksuzian, T. Okusawa, R. Orava, K. Osterberg, S. P. Griso, C. Pagliarone, E. Palencia, V. Papadimitriou, A. Papaikonomou, A. A. Paramanov, B. Parks, S. Pashapour, J. Patrick, G. Pauletta, M. Paulini, C. Paus, T. Peiffer, D. E. Pellett, A. Penzo, T. J. Phillips, G. Piacentino, E. Pianori, L. Pinera, K. Pitts, C. Plager, L. Pondrom, K. Potamianos, O. Poukhov, F. Prokoshin, A. Pronko, F. Ptohos, E. Pueschel, G. Punzi, J. Pursley, J. Rademacker, A. Rahaman, V. Ramakrishnan, N. Ranjan, I. Redondo, P. Renton, M. Renz, M. Rescigno, S. Richter, F. Rimondi, L. Ristori, A. Robson, T. Rodrigo, T. Rodriguez, E. Rogers, S. Rolli, R. Roser, M. Rossi, R. Rossin, P. Roy, A. Ruiz, J. Russ, V. Rusu, B. Rutherford, H. Saarikko, A. Safonov, W. K. Sakumoto, L. Santi, L. Sartori, K. Sato, V. Saveliev, A. Savoy-Navarro, P. Schlabach, A. Schmidt, E. E. Schmidt, M. A. Schmidt, M. P. Schmidt, M. Schmitt, T. Schwarz, L. Scodellaro, A. Scribano, F. Scuri, A. Sedov, S. Seidel, Y. Seiya, A. Semenov, L. Sexton-Kennedy, F. Sforza, A. Sfyrlla, S. Z. Shalhout, T. Shears, P. F. Shepard, M. Shimojima, S. Shiraishi,

M. Shochet, Y. Shon, I. Shreyber, A. Simonenko, P. Sinervo, A. Sisakyan, A. J. Slaughter, J. Slaunwhite, K. Sliwa, J. R. Smith, F. D. Snider, R. Snihur, A. Soha, S. Somalwar, V. Sorin, P. Squillacioti, M. Stanitzki, R. S. Denis, B. Stelzer, O. Stelzer-Chilton, D. Stentz, J. Strologas, G. L. Strycker, J. S. Suh, A. Sukhanov, I. Suslov, A. Taffard, R. Takashima, Y. Takeuchi, R. Tanaka, J. Tang, M. Tecchio, P. K. Teng, J. Thom, J. Thome, G. A. Thompson, E. Thomson, P. Tipton, P. Ttito-Guzman, S. Tkaczyk, D. Toback, S. Tokar, K. Tollefson, T. Tomura, D. Tonelli, S. Torre, D. Torretta, P. Totaro, M. Trovato, S. Y. Tsai, Y. Tu, N. Turini, F. Ukegawa, S. Uozumi, N. van Remortel, A. Varganov, E. Vataga, F. Vazquez, G. Velez, C. Vellidis, M. Vidal, I. Vila, R. Vilar, M. Vogel, I. Volobouev, G. Volpi, P. Wagner, R. G. Wagner, R. L. Wagner, W. Wagner, J. Wagner-Kuhr, T. Wakisaka, R. Wallny, S. M. Wang, A. Warburton, D. Waters, M. Weinberger, J. Weinelt, W. C. Wester, B. Whitehouse, D. Whiteson, A. B. Wicklund, E. Wicklund, S. Wilbur, G. Williams, H. H. Williams, P. Wilson, B. L. Winer, P. Wittich, S. Wolbers, C. Wolfe, H. Wolfe, T. Wright, X. Wu, F. Wurthwein, A. Yagil, K. Yamamoto, J. Yamaoka, U. K. Yang, Y. C. Yang, W. M. Yao, G. P. Yeh, K. Yi, J. Yoh, K. Yorita, T. Yoshida, G. B. Yu, I. Yu, S. S. Yu, J. C. Yun, A. Zanetti, Y. Zeng, X. Zhang, Y. Zheng, and S. Zucchelli

This paper is posted at Purdue e-Pubs.

[http://docs.lib.purdue.edu/physics\\_articles/1081](http://docs.lib.purdue.edu/physics_articles/1081)

**Measurement of  $W$ -Boson Polarization in Top-Quark Decay in  $p\bar{p}$  Collisions at  $\sqrt{s} = 1.96$  TeV**

T. Aaltonen,<sup>25</sup> J. Adelman,<sup>15</sup> B. Álvarez González,<sup>13,x</sup> S. Amerio,<sup>46,45</sup> D. Amidei,<sup>36</sup> A. Anastassov,<sup>40</sup> A. Annovi,<sup>21</sup> J. Antos,<sup>16</sup> G. Apollinari,<sup>19</sup> J. Appel,<sup>19</sup> A. Apresyan,<sup>54</sup> T. Arisawa,<sup>65</sup> A. Artikov,<sup>17</sup> J. Asaadi,<sup>60</sup> W. Ashmanskas,<sup>19</sup> A. Attal,<sup>4</sup> A. Aurisano,<sup>60</sup> F. Azfar,<sup>44</sup> W. Badgett,<sup>19</sup> A. Barbaro-Galtieri,<sup>30</sup> V.E. Barnes,<sup>54</sup> B.A. Barnett,<sup>27</sup> P. Barria,<sup>51,49</sup> P. Bartos,<sup>16</sup> G. Bauer,<sup>34</sup> P.-H. Beauchemin,<sup>35</sup> F. Bedeschi,<sup>49</sup> D. Beecher,<sup>32</sup> S. Behari,<sup>27</sup> G. Bellettini,<sup>50,49</sup> J. Bellinger,<sup>67</sup> D. Benjamin,<sup>18</sup> A. Beretvas,<sup>19</sup> A. Bhatti,<sup>56</sup> M. Binkley,<sup>19,a</sup> D. Bisello,<sup>46,45</sup> I. Bizjak,<sup>32,ee</sup> R.E. Blair,<sup>2</sup> C. Blocker,<sup>8</sup> B. Blumenfeld,<sup>27</sup> A. Bocci,<sup>18</sup> A. Bodek,<sup>55</sup> V. Boisvert,<sup>55</sup> D. Bortoletto,<sup>54</sup> J. Boudreau,<sup>53</sup> A. Boveia,<sup>12</sup> B. Brau,<sup>12,b</sup> A. Bridgeman,<sup>26</sup> L. Brigliadori,<sup>7,6</sup> C. Bromberg,<sup>37</sup> E. Brubaker,<sup>15</sup> J. Budagov,<sup>17</sup> H.S. Budd,<sup>55</sup> S. Budd,<sup>26</sup> K. Burkett,<sup>19</sup> G. Busetto,<sup>46,45</sup> P. Bussey,<sup>23</sup> A. Buzatu,<sup>35</sup> K.L. Byrum,<sup>2</sup> S. Cabrera,<sup>18,z</sup> C. Calancha,<sup>33</sup> S. Camarda,<sup>4</sup> M. Campanelli,<sup>32</sup> M. Campbell,<sup>36</sup> F. Canelli,<sup>15,19</sup> A. Canepa,<sup>48</sup> B. Carls,<sup>26</sup> D. Carlsmith,<sup>67</sup> R. Carosi,<sup>49</sup> S. Carrillo,<sup>20,o</sup> S. Carron,<sup>19</sup> B. Casal,<sup>13</sup> M. Casarsa,<sup>19</sup> A. Castro,<sup>7,6</sup> P. Catastini,<sup>51,49</sup> D. Cauz,<sup>61</sup> V. Cavaliere,<sup>51,49</sup> M. Cavalli-Sforza,<sup>4</sup> A. Cerri,<sup>30</sup> L. Cerrito,<sup>32,r</sup> S.H. Chang,<sup>29</sup> Y.C. Chen,<sup>1</sup> M. Chertok,<sup>9</sup> G. Chiarelli,<sup>49</sup> G. Chlachidze,<sup>19</sup> F. Chlebana,<sup>19</sup> K. Cho,<sup>29</sup> D. Chokheli,<sup>17</sup> J.P. Chou,<sup>24</sup> K. Chung,<sup>19,p</sup> W.H. Chung,<sup>67</sup> Y.S. Chung,<sup>55</sup> T. Chwalek,<sup>28</sup> C.I. Ciobanu,<sup>47</sup> M.A. Ciocchi,<sup>51,49</sup> A. Clark,<sup>22</sup> D. Clark,<sup>8</sup> G. Compstell,<sup>45</sup> M.E. Convery,<sup>19</sup> J. Conway,<sup>9</sup> M. Corbo,<sup>47</sup> M. Cordelli,<sup>21</sup> C.A. Cox,<sup>9</sup> D.J. Cox,<sup>9</sup> F. Crescioli,<sup>50,49</sup> C. Cuenca Almenar,<sup>68</sup> J. Cuevas,<sup>13,x</sup> R. Culbertson,<sup>19</sup> J.C. Cully,<sup>36</sup> D. Dagenhart,<sup>19</sup> N. d'Ascenzo,<sup>47,w</sup> M. Datta,<sup>19</sup> T. Davies,<sup>23</sup> P. de Barbaro,<sup>55</sup> S. De Cecco,<sup>57</sup> A. Deisher,<sup>30</sup> G. De Lorenzo,<sup>4</sup> M. Dell'Orso,<sup>50,49</sup> C. Deluca,<sup>4</sup> L. Demortier,<sup>56</sup> J. Deng,<sup>18,g</sup> M. Deninno,<sup>6</sup> M. d'Errico,<sup>46,45</sup> A. Di Canto,<sup>50,49</sup> B. Di Ruzza,<sup>49</sup> J.R. Dittmann,<sup>5</sup> M. D'Onofrio,<sup>4</sup> S. Donati,<sup>50,49</sup> P. Dong,<sup>19</sup> T. Dorigo,<sup>45</sup> S. Dube,<sup>59</sup> K. Ebina,<sup>65</sup> A. Elagin,<sup>60</sup> R. Erbacher,<sup>9</sup> D. Errede,<sup>26</sup> S. Errede,<sup>26</sup> N. Ershaidat,<sup>47,dd</sup> R. Eusebi,<sup>60</sup> H.C. Fang,<sup>30</sup> S. Farrington,<sup>44</sup> W.T. Fedorko,<sup>15</sup> R.G. Feild,<sup>68</sup> M. Feindt,<sup>28</sup> J.P. Fernandez,<sup>33</sup> C. Ferrazza,<sup>52,49</sup> R. Field,<sup>20</sup> G. Flanagan,<sup>54,t</sup> R. Forrest,<sup>9</sup> M.J. Frank,<sup>5</sup> M. Franklin,<sup>24</sup> J.C. Freeman,<sup>19</sup> I. Furic,<sup>20</sup> M. Gallinaro,<sup>56</sup> J. Galyardt,<sup>14</sup> F. Garbersen,<sup>12</sup> J.E. Garcia,<sup>22</sup> A.F. Garfinkel,<sup>54</sup> P. Garosi,<sup>51,49</sup> H. Gerberich,<sup>26</sup> D. Gerdes,<sup>36</sup> A. Gessler,<sup>28</sup> S. Giagu,<sup>62,61</sup> V. Giakoumopoulou,<sup>3</sup> P. Giannetti,<sup>49</sup> K. Gibson,<sup>53</sup> J.L. Gimmell,<sup>55</sup> C.M. Ginsburg,<sup>19</sup> N. Giokaris,<sup>3</sup> M. Giordani,<sup>62,61</sup> P. Giromini,<sup>21</sup> M. Giunta,<sup>49</sup> G. Giurgiu,<sup>27</sup> V. Glagolev,<sup>17</sup> D. Glenzinski,<sup>19</sup> M. Gold,<sup>39</sup> N. Goldschmidt,<sup>20</sup> A. Golossanov,<sup>19</sup> G. Gomez,<sup>13</sup> G. Gomez-Ceballos,<sup>34</sup> M. Goncharov,<sup>34</sup> O. González,<sup>33</sup> I. Gorelov,<sup>39</sup> A.T. Goshaw,<sup>18</sup> K. Goulianos,<sup>56</sup> A. Gresele,<sup>46,45</sup> S. Grinstein,<sup>4</sup> C. Grosso-Pilcher,<sup>15</sup> R.C. Group,<sup>19</sup> U. Grundler,<sup>26</sup> J. Guimaraes da Costa,<sup>24</sup> Z. Gunay-Unalan,<sup>37</sup> C. Haber,<sup>30</sup> S.R. Hahn,<sup>19</sup> E. Halkiadakis,<sup>59</sup> B.-Y. Han,<sup>55</sup> J.Y. Han,<sup>55</sup> F. Happacher,<sup>21</sup> K. Hara,<sup>63</sup> D. Hare,<sup>59</sup> M. Hare,<sup>64</sup> R.F. Harr,<sup>66</sup> M. Hartz,<sup>53</sup> K. Hatakeyama,<sup>5</sup> C. Hays,<sup>44</sup> M. Heck,<sup>28</sup> J. Heinrich,<sup>48</sup> M. Herndon,<sup>67</sup> J. Heuser,<sup>28</sup> S. Hewamanage,<sup>5</sup> D. Hidas,<sup>59</sup> C.S. Hill,<sup>12,d</sup> D. Hirschbuehl,<sup>28</sup> A. Hocker,<sup>19</sup> S. Hou,<sup>1</sup> M. Houlden,<sup>31</sup> S.-C. Hsu,<sup>30</sup> R.E. Hughes,<sup>41</sup> M. Hurwitz,<sup>15</sup> U. Husemann,<sup>68</sup> M. Hussein,<sup>37</sup> J. Huston,<sup>37</sup> J. Incandela,<sup>12</sup> G. Introzzi,<sup>49</sup> M. Iori,<sup>58,57</sup> A. Ivanov,<sup>9,q</sup> E. James,<sup>19</sup> D. Jang,<sup>14</sup> B. Jayatilaka,<sup>18</sup> E.J. Jeon,<sup>29</sup> M.K. Jha,<sup>6</sup> S. Jindariani,<sup>19</sup> W. Johnson,<sup>9</sup> M. Jones,<sup>54</sup> K.K. Joo,<sup>29</sup> S.Y. Jun,<sup>14</sup> J.E. Jung,<sup>29</sup> T.R. Junk,<sup>19</sup> T. Kamon,<sup>60</sup> D. Kar,<sup>20</sup> P.E. Karchin,<sup>66</sup> Y. Kato,<sup>43,n</sup> R. Kephart,<sup>19</sup> W. Ketchum,<sup>15</sup> J. Keung,<sup>48</sup> V. Khotilovich,<sup>60</sup> B. Kilminster,<sup>19</sup> D.H. Kim,<sup>29</sup> H.S. Kim,<sup>29</sup> H.W. Kim,<sup>29</sup> J.E. Kim,<sup>29</sup> M.J. Kim,<sup>21</sup> S.B. Kim,<sup>29</sup> S.H. Kim,<sup>63</sup> Y.K. Kim,<sup>15</sup> N. Kimura,<sup>65</sup> L. Kirsch,<sup>8</sup> S. Klimenko,<sup>20</sup> K. Kondo,<sup>65</sup> D.J. Kong,<sup>29</sup> J. Konigsberg,<sup>20</sup> A. Korytov,<sup>20</sup> A.V. Kotwal,<sup>18</sup> M. Kreps,<sup>28</sup> J. Kroll,<sup>48</sup> D. Krop,<sup>15</sup> N. Krumnack,<sup>5</sup> M. Kruse,<sup>18</sup> V. Krutelyov,<sup>12</sup> T. Kuhr,<sup>28</sup> N.P. Kulkarni,<sup>66</sup> M. Kurata,<sup>63</sup> S. Kwang,<sup>15</sup> A.T. Laasanen,<sup>54</sup> S. Lami,<sup>49</sup> S. Lammel,<sup>19</sup> M. Lancaster,<sup>32</sup> R.L. Lander,<sup>9</sup> K. Lannon,<sup>41,v</sup> A. Lath,<sup>59</sup> G. Latino,<sup>51,49</sup> I. Lazzizzera,<sup>46,45</sup> T. LeCompte,<sup>2</sup> E. Lee,<sup>60</sup> H.S. Lee,<sup>15</sup> J.S. Lee,<sup>29</sup> S.W. Lee,<sup>60,y</sup> S. Leone,<sup>49</sup> J.D. Lewis,<sup>19</sup> C.-J. Lin,<sup>30</sup> J. Linacre,<sup>44</sup> M. Lindgren,<sup>19</sup> E. Lipeles,<sup>48</sup> A. Lister,<sup>22</sup> D.O. Litvintsev,<sup>19</sup> C. Liu,<sup>53</sup> T. Liu,<sup>19</sup> N.S. Lockyer,<sup>48</sup> A. Loginov,<sup>68</sup> L. Lovas,<sup>16</sup> D. Lucchesi,<sup>46,45</sup> J. Lueck,<sup>28</sup> P. Lujan,<sup>30</sup> P. Lukens,<sup>19</sup> G. Lungu,<sup>56</sup> J. Lys,<sup>30</sup> R. Lysak,<sup>16</sup> D. MacQueen,<sup>35</sup> R. Madrak,<sup>19</sup> K. Maeshima,<sup>19</sup> K. Makhoul,<sup>34</sup> P. Maksimovic,<sup>27</sup> S. Malde,<sup>44</sup> S. Malik,<sup>32</sup> G. Manca,<sup>31,f</sup> A. Manousakis-Katsikakis,<sup>3</sup> F. Margaroli,<sup>54</sup> C. Marino,<sup>28</sup> C.P. Marino,<sup>26</sup> A. Martin,<sup>68</sup> V. Martin,<sup>23,1</sup> M. Martínez,<sup>4</sup> R. Martínez-Ballarín,<sup>33</sup> P. Mastrandrea,<sup>57</sup> M. Mathis,<sup>27</sup> M.E. Mattson,<sup>66</sup> P. Mazzanti,<sup>6</sup> K.S. McFarland,<sup>55</sup> P. McIntyre,<sup>60</sup> R. McNulty,<sup>31,k</sup> A. Mehta,<sup>31</sup> P. Mehtala,<sup>25</sup> A. Menzione,<sup>49</sup> C. Mesropian,<sup>56</sup> T. Miao,<sup>19</sup> D. Mietlicki,<sup>36</sup> N. Miladinovic,<sup>8</sup> R. Miller,<sup>37</sup> C. Mills,<sup>24</sup> M. Milnik,<sup>28</sup> A. Mitra,<sup>1</sup> G. Mitselmakher,<sup>20</sup> H. Miyake,<sup>63</sup> S. Moed,<sup>24</sup> N. Moggi,<sup>6</sup> M.N. Mondragon,<sup>19,o</sup> C.S. Moon,<sup>29</sup> R. Moore,<sup>19</sup> M.J. Morello,<sup>49</sup> J. Morlock,<sup>28</sup> P. Movilla Fernandez,<sup>19</sup> J. Mülmenstädt,<sup>30</sup> A. Mukherjee,<sup>19</sup> Th. Muller,<sup>19</sup> P. Murat,<sup>19</sup> M. Mussini,<sup>7,6</sup> J. Nachtman,<sup>19,p</sup> Y. Nagai,<sup>63</sup> J. Naganoma,<sup>63</sup> K. Nakamura,<sup>63</sup> I. Nakano,<sup>42</sup> A. Napier,<sup>64</sup> J. Nett,<sup>67</sup> C. Neu,<sup>48,bb</sup> M.S. Neubauer,<sup>26</sup> S. Neubauer,<sup>28</sup> J. Nielsen,<sup>30,h</sup> L. Nodulman,<sup>2</sup> M. Norman,<sup>11</sup> O. Norniella,<sup>26</sup> E. Nurse,<sup>32</sup> L. Oakes,<sup>44</sup> S.H. Oh,<sup>18</sup> Y.D. Oh,<sup>29</sup> I. Oksuzian,<sup>20</sup> T. Okusawa,<sup>43</sup> R. Orava,<sup>25</sup> K. Osterberg,<sup>25</sup> S. Pagan Griso,<sup>46,45</sup> C. Pagliarone,<sup>61</sup> E. Palencia,<sup>19</sup> V. Papadimitriou,<sup>19</sup> A. Papaikonomou,<sup>28</sup>

A. A. Paramanov,<sup>2</sup> B. Parks,<sup>41</sup> S. Pashapour,<sup>35</sup> J. Patrick,<sup>19</sup> G. Pauletta,<sup>62,61</sup> M. Paulini,<sup>14</sup> C. Paus,<sup>34</sup> T. Peiffer,<sup>28</sup> D. E. Pellett,<sup>9</sup> A. Penzo,<sup>61</sup> T. J. Phillips,<sup>18</sup> G. Piacentino,<sup>49</sup> E. Pianori,<sup>48</sup> L. Pinera,<sup>20</sup> K. Pitts,<sup>26</sup> C. Plager,<sup>10</sup> L. Pondrom,<sup>67</sup> K. Potamianos,<sup>54</sup> O. Poukhov,<sup>17,a</sup> F. Prokoshin,<sup>17,aa</sup> A. Pronko,<sup>19</sup> F. Ptohos,<sup>19,j</sup> E. Pueschel,<sup>14</sup> G. Punzi,<sup>50,49</sup> J. Pursley,<sup>67</sup> J. Rademacker,<sup>44,d</sup> A. Rahaman,<sup>53</sup> V. Ramakrishnan,<sup>67</sup> N. Ranjan,<sup>54</sup> I. Redondo,<sup>33</sup> P. Renton,<sup>44</sup> M. Renz,<sup>28</sup> M. Rescigno,<sup>57</sup> S. Richter,<sup>28</sup> F. Rimondi,<sup>7,6</sup> L. Ristori,<sup>49</sup> A. Robson,<sup>23</sup> T. Rodrigo,<sup>13</sup> T. Rodriguez,<sup>48</sup> E. Rogers,<sup>26</sup> S. Rolli,<sup>64</sup> R. Roser,<sup>19</sup> M. Rossi,<sup>61</sup> R. Rossin,<sup>12</sup> P. Roy,<sup>35</sup> A. Ruiz,<sup>13</sup> J. Russ,<sup>14</sup> V. Rusu,<sup>19</sup> B. Rutherford,<sup>19</sup> H. Saarikko,<sup>25</sup> A. Safonov,<sup>60</sup> W. K. Sakumoto,<sup>55</sup> L. Santi,<sup>62,61</sup> L. Sartori,<sup>49</sup> K. Sato,<sup>63</sup> V. Saveliev,<sup>47,w</sup> A. Savoy-Navarro,<sup>47</sup> P. Schlabach,<sup>19</sup> A. Schmidt,<sup>28</sup> E. E. Schmidt,<sup>19</sup> M. A. Schmidt,<sup>15</sup> M. P. Schmidt,<sup>68,a</sup> M. Schmitt,<sup>40</sup> T. Schwarz,<sup>9</sup> L. Scodellaro,<sup>13</sup> A. Scribano,<sup>51,49</sup> F. Scuri,<sup>49</sup> A. Sedov,<sup>54</sup> S. Seidel,<sup>39</sup> Y. Seiya,<sup>43</sup> A. Semenov,<sup>17</sup> L. Sexton-Kennedy,<sup>19</sup> F. Sforza,<sup>50,49</sup> A. Sfyrly,<sup>26</sup> S. Z. Shalhout,<sup>66</sup> T. Shears,<sup>31</sup> P. F. Shepard,<sup>53</sup> M. Shimojima,<sup>63,u</sup> S. Shiraishi,<sup>15</sup> M. Shochet,<sup>15</sup> Y. Shon,<sup>67</sup> I. Shreyber,<sup>38</sup> A. Simonenko,<sup>17</sup> P. Sinervo,<sup>35</sup> A. Sisakyan,<sup>17</sup> A. J. Slaughter,<sup>19</sup> J. Slaunwhite,<sup>41</sup> K. Sliwa,<sup>64</sup> J. R. Smith,<sup>9</sup> F. D. Snider,<sup>19</sup> R. Snihur,<sup>35</sup> A. Soha,<sup>19</sup> S. Somalwar,<sup>59</sup> V. Sorin,<sup>4</sup> P. Squillacioti,<sup>51,49</sup> M. Stanitzki,<sup>68</sup> R. St. Denis,<sup>23</sup> B. Stelzer,<sup>35</sup> O. Stelzer-Chilton,<sup>35</sup> D. Stentz,<sup>40</sup> J. Strologas,<sup>39</sup> G. L. Strycker,<sup>36</sup> J. S. Suh,<sup>29</sup> A. Sukhanov,<sup>20</sup> I. Suslov,<sup>17</sup> A. Taffard,<sup>26,g</sup> R. Takashima,<sup>42</sup> Y. Takeuchi,<sup>63</sup> R. Tanaka,<sup>42</sup> J. Tang,<sup>15</sup> M. Tecchio,<sup>36</sup> P. K. Teng,<sup>1</sup> J. Thom,<sup>19,i</sup> J. Thome,<sup>14</sup> G. A. Thompson,<sup>26</sup> E. Thomson,<sup>48</sup> P. Tipton,<sup>68</sup> P. Tito-Guzmán,<sup>33</sup> S. Tkaczyk,<sup>19</sup> D. Toback,<sup>60</sup> S. Tokar,<sup>16</sup> K. Tollefson,<sup>37</sup> T. Tomura,<sup>63</sup> D. Tonelli,<sup>19</sup> S. Torre,<sup>21</sup> D. Torretta,<sup>19</sup> P. Totaro,<sup>62,61</sup> M. Trovato,<sup>52,49</sup> S.-Y. Tsai,<sup>1</sup> Y. Tu,<sup>48</sup> N. Turini,<sup>51,49</sup> F. Ukegawa,<sup>63</sup> S. Uozumi,<sup>29</sup> N. van Remortel,<sup>25,c</sup> A. Varganov,<sup>36</sup> E. Vataga,<sup>52,49</sup> F. Vázquez,<sup>20,o</sup> G. Velev,<sup>19</sup> C. Vellidis,<sup>3</sup> M. Vidal,<sup>33</sup> I. Vila,<sup>13</sup> R. Vilar,<sup>13</sup> M. Vogel,<sup>39</sup> I. Volobouev,<sup>30,y</sup> G. Volpi,<sup>50,49</sup> P. Wagner,<sup>48</sup> R. G. Wagner,<sup>2</sup> R. L. Wagner,<sup>19</sup> W. Wagner,<sup>28,cc</sup> J. Wagner-Kuhr,<sup>28</sup> T. Wakisaka,<sup>43</sup> R. Wallny,<sup>10</sup> S. M. Wang,<sup>1</sup> A. Warburton,<sup>35</sup> D. Waters,<sup>32</sup> M. Weinberger,<sup>60</sup> J. Weinelt,<sup>28</sup> W. C. Wester III,<sup>19</sup> B. Whitehouse,<sup>64</sup> D. Whiteson,<sup>48,g</sup> A. B. Wicklund,<sup>2</sup> E. Wicklund,<sup>19</sup> S. Wilbur,<sup>15</sup> G. Williams,<sup>35</sup> H. H. Williams,<sup>48</sup> P. Wilson,<sup>19</sup> B. L. Winer,<sup>41</sup> P. Wittich,<sup>19,i</sup> S. Wolbers,<sup>19</sup> C. Wolfe,<sup>15</sup> H. Wolfe,<sup>41</sup> T. Wright,<sup>36</sup> X. Wu,<sup>22</sup> F. Würthwein,<sup>11</sup> A. Yagil,<sup>11</sup> K. Yamamoto,<sup>43</sup> J. Yamaoka,<sup>18</sup> U. K. Yang,<sup>15,s</sup> Y. C. Yang,<sup>29</sup> W. M. Yao,<sup>30</sup> G. P. Yeh,<sup>19</sup> K. Yi,<sup>19,p</sup> J. Yoh,<sup>19</sup> K. Yorita,<sup>65</sup> T. Yoshida,<sup>43,m</sup> G. B. Yu,<sup>18</sup> I. Yu,<sup>29</sup> S. S. Yu,<sup>19</sup> J. C. Yun,<sup>19</sup> A. Zanetti,<sup>61</sup> Y. Zeng,<sup>18</sup> X. Zhang,<sup>26</sup> Y. Zheng,<sup>10,e</sup> and S. Zucchelli<sup>7,6</sup>

(CDF Collaboration)

<sup>1</sup>*Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*<sup>2</sup>*Argonne National Laboratory, Argonne, Illinois 60439, USA*<sup>3</sup>*University of Athens, 157 71 Athens, Greece*<sup>4</sup>*Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, E-08193, Bellaterra (Barcelona), Spain*<sup>5</sup>*Baylor University, Waco, Texas 76798, USA*<sup>6</sup>*Istituto Nazionale di Fisica Nucleare Bologna, I-40127 Bologna, Italy*<sup>7</sup>*University of Bologna, I-40127 Bologna, Italy*<sup>8</sup>*Brandeis University, Waltham, Massachusetts 02254, USA*<sup>9</sup>*University of California, Davis, Davis, California 95616, USA*<sup>10</sup>*University of California, Los Angeles, Los Angeles, California 90024, USA*<sup>11</sup>*University of California, San Diego, La Jolla, California 92093, USA*<sup>12</sup>*University of California, Santa Barbara, Santa Barbara, California 93106, USA*<sup>13</sup>*Instituto de Física de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*<sup>14</sup>*Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA*<sup>15</sup>*Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637, USA*<sup>16</sup>*Comenius University, 842 48 Bratislava, Slovakia; Institute of Experimental Physics, 040 01 Kosice, Slovakia*<sup>17</sup>*Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*<sup>18</sup>*Duke University, Durham, North Carolina 27708, USA*<sup>19</sup>*Fermi National Accelerator Laboratory, Batavia, Illinois 60510, USA*<sup>20</sup>*University of Florida, Gainesville, Florida 32611, USA*<sup>21</sup>*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*<sup>22</sup>*University of Geneva, CH-1211 Geneva 4, Switzerland*<sup>23</sup>*Glasgow University, Glasgow G12 8QQ, United Kingdom*<sup>24</sup>*Harvard University, Cambridge, Massachusetts 02138, USA*<sup>25</sup>*Division of High Energy Physics, Department of Physics, University of Helsinki and Helsinki Institute of Physics, FIN-00014, Helsinki, Finland*<sup>26</sup>*University of Illinois, Urbana, Illinois 61801, USA*<sup>27</sup>*The Johns Hopkins University, Baltimore, Maryland 21218, USA*<sup>28</sup>*Institut für Experimentelle Kernphysik, Karlsruhe Institute of Technology, D-76131 Karlsruhe, Germany*

- <sup>29</sup>*Center for High Energy Physics: Kyungpook National University, Daegu 702-701, Korea;  
Seoul National University, Seoul 151-742, Korea;  
Sungkyunkwan University, Suwon 440-746, Korea;  
Korea Institute of Science and Technology Information, Daejeon 305-806, Korea;  
Chonnam National University, Gwangju 500-757, Korea;  
Chonbuk National University, Jeonju 561-756, Korea*
- <sup>30</sup>*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
- <sup>31</sup>*University of Liverpool, Liverpool L69 7ZE, United Kingdom*
- <sup>32</sup>*University College London, London WC1E 6BT, United Kingdom*
- <sup>33</sup>*Centro de Investigaciones Energeticas Medioambientales y Tecnologicas, E-28040 Madrid, Spain*
- <sup>34</sup>*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139, USA*
- <sup>35</sup>*Institute of Particle Physics: McGill University, Montréal, Québec, Canada H3A 2T8;  
Simon Fraser University, Burnaby, British Columbia, Canada V5A 1S6;  
University of Toronto, Toronto, Ontario, Canada M5S 1A7;  
and TRIUMF, Vancouver, British Columbia, Canada V6T 2A3*
- <sup>36</sup>*University of Michigan, Ann Arbor, Michigan 48109, USA*
- <sup>37</sup>*Michigan State University, East Lansing, Michigan 48824, USA*
- <sup>38</sup>*Institution for Theoretical and Experimental Physics, ITEP, Moscow 117259, Russia*
- <sup>39</sup>*University of New Mexico, Albuquerque, New Mexico 87131, USA*
- <sup>40</sup>*Northwestern University, Evanston, Illinois 60208, USA*
- <sup>41</sup>*The Ohio State University, Columbus, Ohio 43210, USA*
- <sup>42</sup>*Okayama University, Okayama 700-8530, Japan*
- <sup>43</sup>*Osaka City University, Osaka 588, Japan*
- <sup>44</sup>*University of Oxford, Oxford OX1 3RH, United Kingdom*
- <sup>45</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Padova-Trento, I-35131 Padova, Italy*
- <sup>46</sup>*University of Padova, I-35131 Padova, Italy*
- <sup>47</sup>*LPNHE, Universite Pierre et Marie Curie/IN2P3-CNRS, UMR7585, Paris, F-75252 France*
- <sup>48</sup>*University of Pennsylvania, Philadelphia, Pennsylvania 19104, USA*
- <sup>49</sup>*Istituto Nazionale di Fisica Nucleare Pisa, I-56127 Pisa, Italy*
- <sup>50</sup>*University of Pisa, I-56127 Pisa, Italy*
- <sup>51</sup>*University of Siena, I-56127 Pisa, Italy*
- <sup>52</sup>*Scuola Normale Superiore, I-56127 Pisa, Italy*
- <sup>53</sup>*University of Pittsburgh, Pittsburgh, Pennsylvania 15260, USA*
- <sup>54</sup>*Purdue University, West Lafayette, Indiana 47907, USA*
- <sup>55</sup>*University of Rochester, Rochester, New York 14627, USA*
- <sup>56</sup>*The Rockefeller University, New York, New York 10021, USA*
- <sup>57</sup>*Istituto Nazionale di Fisica Nucleare, Sezione di Roma 1, I-00185 Roma, Italy*
- <sup>58</sup>*Sapienza Università di Roma, I-00185 Roma, Italy*
- <sup>59</sup>*Rutgers University, Piscataway, New Jersey 08855, USA*
- <sup>60</sup>*Texas A&M University, College Station, Texas 77843, USA*
- <sup>61</sup>*Istituto Nazionale di Fisica Nucleare Trieste/Udine, I-34100 Trieste, I-33100 Udine, Italy*
- <sup>62</sup>*University of Trieste/Udine, I-33100 Udine, Italy*
- <sup>63</sup>*University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
- <sup>64</sup>*Tufts University, Medford, Massachusetts 02155, USA*
- <sup>65</sup>*Waseda University, Tokyo 169, Japan*
- <sup>66</sup>*Wayne State University, Detroit, Michigan 48201, USA*
- <sup>67</sup>*University of Wisconsin, Madison, Wisconsin 53706, USA*
- <sup>68</sup>*Yale University, New Haven, Connecticut 06520, USA*
- (Received 2 March 2010; published 23 July 2010)

We report measurements of the polarization of  $W$  bosons from top-quark decays using  $2.7 \text{ fb}^{-1}$  of  $p\bar{p}$  collisions collected by the CDF II detector. Assuming a top-quark mass of  $175 \text{ GeV}/c^2$ , three measurements are performed. A simultaneous measurement of the fraction of longitudinal ( $f_0$ ) and right-handed ( $f_+$ )  $W$  bosons yields the model-independent results  $f_0 = 0.88 \pm 0.11(\text{stat}) \pm 0.06(\text{syst})$  and  $f_+ = -0.15 \pm 0.07(\text{stat}) \pm 0.06(\text{syst})$  with a correlation coefficient of  $-0.59$ . A measurement of  $f_0$  [ $f_+$ ] constraining  $f_+$  [ $f_0$ ] to its standard model value of  $0.0$  [ $0.7$ ] yields  $f_0 = 0.70 \pm 0.07(\text{stat}) \pm 0.04(\text{syst})$  [ $f_+ = -0.01 \pm 0.02(\text{stat}) \pm 0.05(\text{syst})$ ]. All these results are consistent with standard model expectations. We achieve the single most precise measurements of  $f_0$  for both the model-independent and model-dependent determinations.



The top quark is the most massive fundamental particle observed by experiment [1]. Because of its large mass, in the standard model (SM) the top quark decays before forming a bound state via the charged current weak interaction into a  $W^+$  boson and a  $b$  quark [2], with a branching fraction above 99% [3]. This provides a unique opportunity to study the properties of a “bare” quark. In particular, the  $V$ - $A$  structure of the weak interaction can be tested by reconstructing the polarization of the  $W^+$  boson from top-quark decay. In the SM at tree level [4], the  $W^+$  boson is expected to have longitudinal polarization  $f_0 = 0.703$ , left-handed polarization  $f_- = 0.297$ , and right-handed polarization  $f_+ = 3.6 \times 10^{-4}$  for a top-quark mass  $m_t = 175 \text{ GeV}/c^2$ , a  $W$ -boson mass  $M_W = 80.413 \text{ GeV}/c^2$  [5], and a  $b$ -quark mass  $m_b = 4.79 \text{ GeV}/c^2$  [3]. In the limit of  $m_b \rightarrow 0$ ,  $f_0 = m_t^2/(2m_W^2 + m_t^2)$  and  $f_+ = 0$ . The higher-order QCD and electroweak radiative corrections modify these predictions at the 1%–2% (relative) level [6]. In beyond-the-SM scenarios, significant deviations from the SM expectation are possible due to the presence of anomalous couplings [4] in the  $tWb$  vertex. Measurements of  $W$ -boson polarization and single top-quark production together set constraints on the anomalous coupling vector and tensor form factors [7].

In this Letter, we measure the polarization of the  $W$  boson from top-quark decay. We assume the  $t\bar{t}$  production mechanism is in agreement with the SM, and we study a data sample enriched in  $t\bar{t} \rightarrow W^+bW^-\bar{b} \rightarrow \ell\nu bq\bar{q}'\bar{b}$  events where one of the  $W$  bosons decays hadronically and the other leptonically (lepton plus jets). We apply a likelihood technique based on the theoretical matrix elements for both the dominant signal process,  $q\bar{q} \rightarrow t\bar{t}$ , and the main background process, inclusive production of  $W$  + jets. This technique was first developed for the measurements of top-quark mass and  $f_0$ , constraining  $f_+$  to its SM value [8], and utilizes the kinematic and topological information from the event through integrations over poorly known parton-level quantities. We express the matrix element in terms of the  $W$ -boson polarization fractions and the cosine of the angle  $\theta^*$  between the momentum of the charged lepton or down-type quark in the  $W$ -boson rest frame and the momentum of the  $W$  boson in the top-quark rest frame. Therefore we extract information on the  $W$ -boson polarization from both the leptonic and hadronic  $W$ -boson decays. Previous CDF measurements [9,10] used only information from the leptonic decay. While the information from the hadronic  $W$ -boson decay carries a sign ambiguity in  $\cos\theta^*$  since we are unable to identify the down-type quark jet its inclusion still improves the sensitivity to the  $f_0$  polarization fraction. The analysis described in this Letter improves the statistical sensitivity on  $f_0$  by 20% relative to the best previous CDF measurement [9] for the same event sample. The latest D0 measurement also utilizes information from both the leptonic and hadronic  $W$ -boson decays [11].

We report measurements of the  $W$ -boson polarization for three different hypotheses of top-quark decay: (i) model-independent with simultaneous measurement of  $f_0$  and  $f_+$ ; (ii) anomalous tensor couplings with measurement of  $f_0$  for fixed  $f_+ = 0$ ; and (iii) anomalous right-handed couplings with measurement of  $f_+$  for fixed  $f_0 = 0.70$ .

The polarization fractions are determined using an unbinned likelihood function  $L$  maximized with respect to  $f_0$ ,  $f_+$ , and the fraction of events consistent with the  $t\bar{t}$  signal hypothesis,  $C_s$ ,

$$L(f_0, f_+, C_s) = \prod_{i=1}^N \left[ C_s \frac{P_s(x; f_0, f_+)}{\langle A_s(x; f_0, f_+) \rangle} + (1 - C_s) \times \frac{P_b(x)}{\langle A_b(x) \rangle} \right].$$

Here,  $N$  is the number of observed events,  $x$  is a set of observed variables, and  $\langle A_s \rangle$  and  $\langle A_b \rangle$  refer to the average acceptances for  $t\bar{t}$  and  $W$  + jets background events, respectively. The dependence of the  $t\bar{t}$  signal acceptance on the polarization fractions is accounted for in  $\langle A_s \rangle$ . The signal probability  $P_s$  and background probability  $P_b$  densities are constructed as in [12] by integrating over the appropriate parton-level differential cross section convolved with the proton parton distribution functions (PDFs). The parton four momenta are estimated from the single lepton and the four highest transverse energy  $E_T$  [13] jets in the event, and transfer functions derived from Monte Carlo (MC) are used to unfold the detector resolution effects. There is an ambiguity in the jet-parton assignments and all permutations are used for each event.

The signal differential cross section uses the leading-order matrix element of the  $q\bar{q} \rightarrow t\bar{t}$  process [14], expressed in terms of  $\cos\theta^*$  and the polarization fractions:

$$|M|^2 = \frac{g_s^4}{9} F_\ell \bar{F}_h (2 - \beta^2 \sin^2 \theta_{q\ell}),$$

where  $g_s$  is the strong coupling constant,  $\theta_{q\ell}$  describes the angle between the incoming parton and the top quark in the rest frame of the incoming partons, and  $\beta$  is the velocity of the top quarks in the same rest frame. The factors  $F_\ell$  and  $\bar{F}_h$  correspond to the top quarks with a leptonic and a hadronic  $W$ -boson decay, such that

$$F_\ell = \frac{2\pi g_W^4 m_{\ell\nu}^2}{3m_t \Gamma_t} (2E_b^{*2} + 3E_b^* m_{\ell\nu} + m_b^2) \left[ \frac{3}{8} (1 + \cos\theta^*)^2 f_+ + \frac{3}{4} (1 - \cos^2\theta^*) f_0 + \frac{3}{8} (1 - \cos\theta^*)^2 (1 - f_0 - f_+) \right].$$

Here  $g_W$  is the weak coupling constant,  $m_{\ell\nu}$  is the invariant mass of the lepton and neutrino,  $\Gamma_t$  is the width of the top quark,  $m_t$  and  $m_b$  are the masses of the top quark and  $b$  quark, respectively, and  $E_b^* = \frac{m_t^2 - m_b^2 - m_{\ell\nu}^2}{2m_{\ell\nu}}$ . The hadronic factor  $\bar{F}_h$  is similar, with the exception that we do not

distinguish between up-type and down-type quarks from  $W$ -boson decay and use the average  $\bar{F}_h$  related to the two permutations. The background differential cross section uses the sum of matrix elements for  $W$  + jets from the VECBOS [15] MC generator.

The measurement is based on a data set with an integrated luminosity of  $2.7 \text{ fb}^{-1}$  acquired by the collider detector at Fermilab (CDF II) [16] from  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96 \text{ TeV}$ . The data used are collected using high-transverse momentum ( $p_T$ ) [13] central (pseudorapidity  $|\eta| < 1.1$ ) electron and muon triggers, a high- $p_T$  forward ( $1.2 < |\eta| < 2.0$ ) electron trigger, and a trigger that requires large missing transverse energy  $\cancel{E}_T$  [13] with either an energetic electromagnetic cluster or two separated jets ( $\cancel{E}_T$  + jets) [17]. The  $\cancel{E}_T$  + jets trigger is used to select additional events with high- $p_T$  muons, which are not selected by the lepton triggers.

Candidate events for the lepton plus jets final state are selected to have a single, isolated electron or muon candidate with  $E_T > 20 \text{ GeV}$ , large  $\cancel{E}_T$  in the event ( $\cancel{E}_T > 20 \text{ GeV}$ ) as expected from the undetectable neutrino, and at least four jets with  $E_T > 20 \text{ GeV}$ . Jets are reconstructed using a cone algorithm with radius  $\Delta R = 0.4$  in  $\eta - \phi$  space, and their energies are corrected for nonuniformities in the calorimeter response as a function of jet  $\eta$ , multiple  $p\bar{p}$  interactions, and the hadronic jet energy scale of the calorimeter [18]. Of these jets, we require at least one to have originated from a  $b$  quark by using an algorithm that identifies a long-lived  $b$  hadron through the presence of a displaced vertex ( $b$  tag) [19]. Backgrounds to the  $t\bar{t}$  signal arise from multijet QCD production (QCD),  $W$ -boson production in association with jets ( $W$  + jets), and electroweak backgrounds (EWK) composed of diboson ( $WW$ ,  $WZ$ ,  $ZZ$ ) and single top-quark production. The  $W$  + jets background includes  $b$ -flavor jets as well as light flavor jets incorrectly identified as  $b$  jets.

A detailed description of the background estimation can be found in Ref. [20]. Table I shows the expected sample composition assuming a  $t\bar{t}$  cross section of  $6.7 \text{ pb}$ . There are overlapping events between those collected by the high- $p_T$  lepton triggers and the  $\cancel{E}_T$  + jets trigger which are included in the central  $e/\mu$  and forward  $e$  categories, and are eliminated from the  $\cancel{E}_T$  + jets category.

The HERWIG [21] MC generator is used to model the  $t\bar{t}$  signal events with  $m_t = 175 \text{ GeV}/c^2$ . For estimation of various systematic uncertainties and background modeling MC samples are created using the PYTHIA [22] generator, and ALPGEN [23] or MADEVENT [24] with PYTHIA or HERWIG supplying the parton shower and fragmentation. The QCD background is modeled using data control samples. The signal and background modeling has been extensively checked. Figure 1 compares the observed data and the MC-predicted distributions of different kinematic variables. We have validated the background model by studying a high-statistics control sample of  $W$  + jets can-

TABLE I. Number of expected and observed events in  $2.7 \text{ fb}^{-1}$  assuming a  $t\bar{t}$  cross section of  $6.7 \text{ pb}$ .

Process	Central	Forward	$\cancel{E}_T$ + jets
	$e, \mu$	$e$	$\mu$
$t\bar{t}$	$478 \pm 66$	$58 \pm 8$	$134 \pm 19$
$W$ + jets	$94 \pm 23$	$18 \pm 11$	$25 \pm 6$
EWK	$17 \pm 10$	$3 \pm 1$	$5 \pm 3$
QCD	$28 \pm 22$	$46 \pm 37$	$1 \pm 1$
Total expected	$616 \pm 74$	$125 \pm 40$	$165 \pm 20$
Observed	650	136	178

didates extracted by vetoing events containing  $b$ -tagged jets.

We calibrate the results of the likelihood fit using the simulated  $t\bar{t}$  and background samples, and the sample composition of Table I. For the simultaneous measurement of  $f_0$  and  $f_+$ , we find our estimate  $f_{0,m}$  is related to the true value of  $f_0$  by  $f_{0,m} = (0.88 \pm 0.02)f_0 + (-0.12 \pm 0.01)$  and our estimate of  $f_{+,m}$  is related to the true value of  $f_+$  and  $f_0$  by  $f_{+,m} = (1.26 \pm 0.01)f_+ + (0.17 \pm 0.02)f_0 + (0.06 \pm 0.01)$ . We use these calibration functions and the measured polarization fractions to extract the true polarization fractions. For our measurement of  $f_0$  with  $f_+ = 0$ , we find our estimate  $f_{0,m} = (1.15 \pm 0.04)f_0 + (-0.09 \pm 0.02)$ , and for our measurement of  $f_+$  with  $f_0 = 0.7$ , we

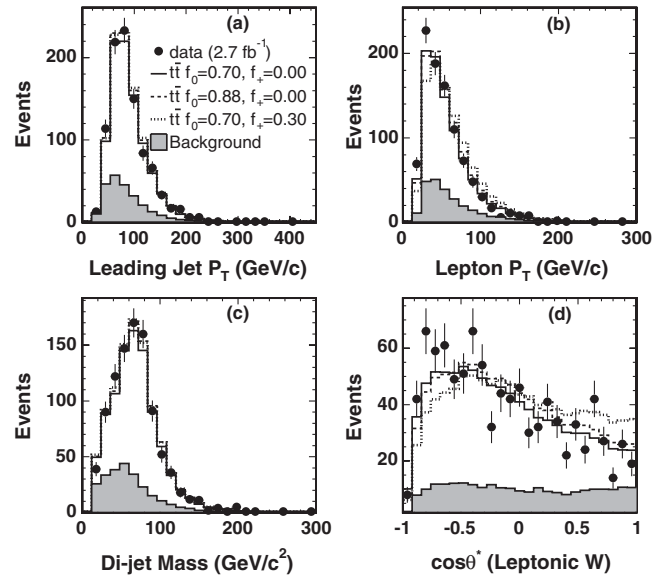


FIG. 1. Comparison of four kinematic variables for data and simulation for different  $W$  polarization fractions: solid, dashed and dotted histograms correspond to  $(f_0, f_+)$  values of (0.7, 0.0), (0.88, 0.0), and (0.7, 0.3), respectively. Plotted are (a) leading jet  $p_T$ , (b) lepton  $p_T$ ; and for the reconstruction chosen as most likely by the per-event likelihood (c) the invariant mass of the pair of light quark jets from the hadronically decaying  $W$  boson and (d) the  $\cos\theta^*$  of the leptonically decaying  $W$  boson.



TABLE II. Summary of systematic uncertainties.

Source	$\Delta f_0$	$\Delta f_+$	$\Delta f_0$ and $\Delta f_+$ simultaneous	
			$\Delta f_0$	$\Delta f_+$
ISR or FSR	0.020	0.018	0.020	0.021
PDF	0.024	0.013	0.009	0.016
JES	0.018	0.017	0.004	0.012
Parton shower	0.012	0.008	0.031	0.017
Background	0.009	0.038	0.042	0.039
Method-related	0.010	0.005	0.024	0.024
Total	0.041	0.048	0.062	0.057

find our estimate  $f_{+,m} = (1.17 \pm 0.05)f_+ + (0.01 \pm 0.01)$ . The uncertainties on the coefficients of the calibration functions are included in the method-related systematic uncertainties, which cover possible biases due to the calibration procedure. The differences between our measured values and the true values arise because the signal and background probabilities used in the likelihood do not accurately model the effects of extra jets arising from initial and final state radiation (ISR/FSR) nor the full set of contributing background processes. Even though likelihood can be calculated only for the physical values of  $f_0$  and  $f_+$ , after calibration the corrected measured values can be slightly outside their physical ranges.

The robustness of the fitting procedure over all physical values of  $(f_0, f_+)$  has been tested with simulated experiments, using the number of observed data events and the sample composition of Table I. In all cases, the method is unbiased. Near the physical boundaries, we find that the statistical uncertainty is underestimated by as much as a factor of 1.5. We apply a correction to the statistical uncertainty in these regions. Assuming the SM, the expected statistical uncertainties after all corrections for the simultaneous measurement are  $\pm 0.116$  and  $\pm 0.074$  for  $f_0$  and  $f_+$ , respectively.

Various sources of systematic uncertainty affecting the measurement are summarized in Table II. The leading sources of systematic uncertainty arise from MC modeling of initial and final state radiation (ISR and FSR), choice of PDFs, choice of parton shower model, uncertainties on the measured jet energy, and the background shape and normalization. The method-related uncertainty includes propagating the uncertainty on the fit parameters of the calibration functions, including their correlations. All systematic uncertainties are determined by performing simulated experiments in which the systematic parameter in question is varied, the default method and calibrations are applied, and the shifts in the mean measured polarization fractions are used to quantify the uncertainty. All shifts are evaluated at the SM helicity fraction.

For the simultaneous measurement of  $f_0$  and  $f_+$ , we exclude the events from the forward electron trigger as this significantly reduces the systematic uncertainty from the background model. With 828 events and after all correc-

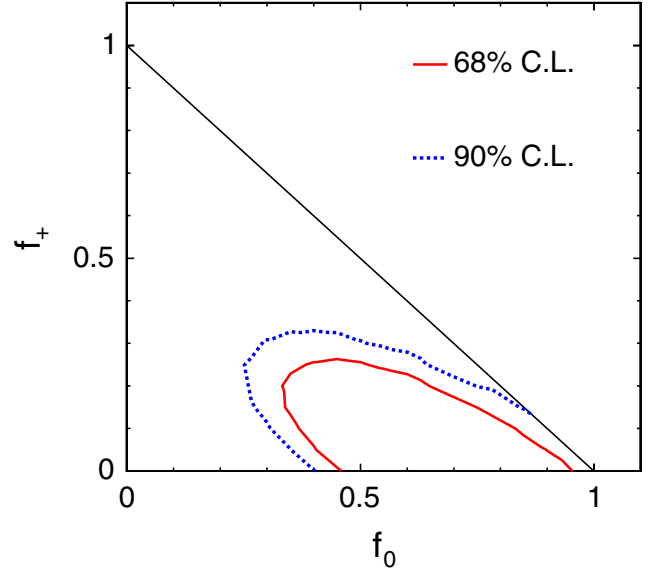


FIG. 2 (color online). Contours in the  $(f_0, f_+)$  plane indicating 68% and 90% C.L. intervals determined using the Feldman-Cousins method. Note that the coverage is correct although the center of the contours is not at the measured value obtained after calibration.

tions, we measure

$$f_0 = 0.879 \pm 0.106(\text{stat}) \pm 0.062(\text{syst}),$$

$$f_+ = -0.151 \pm 0.067(\text{stat}) \pm 0.057(\text{syst}).$$

The statistical correlation between  $f_0$  and  $f_+$  is  $\rho = -0.59$ . We estimate a shift of  $\mp(0.010 \pm 0.005)$  in  $f_0$  and  $\pm(0.017 \pm 0.003)$  in  $f_+$  per  $\pm 1$  GeV/ $c^2$  shift in the top-quark mass from the central value of 175 GeV/ $c^2$ . As the central value is unphysical we have elected to ensure coverage by applying the Feldman-Cousins method [25] to obtain the confidence level (C.L.) intervals shown in Fig. 2.

Fixing  $f_+ = 0$  and with 964 events, we measure after all corrections  $f_0 = 0.701 \pm 0.069(\text{stat}) \pm 0.041(\text{syst})$ . Fixing  $f_0 = 0.70$ , we measure after all corrections  $f_+ = -0.010 \pm 0.019(\text{stat}) \pm 0.049(\text{syst})$  and find  $f_+ < 0.12$  at 95% C.L. We estimate a shift of  $\pm(0.011 \pm 0.003)$  in  $f_0$  and  $\pm(0.013 \pm 0.002)$  in  $f_+$  per  $\pm 1$  GeV/ $c^2$  shift in the top-quark mass from the central value of 175 GeV/ $c^2$ .

In summary, we have measured the polarization of the  $W$  boson in top-quark decays using a matrix-element method in  $2.7 \text{ fb}^{-1}$  of CDF II data. Our results are consistent with the SM. This result improves the combined statistical and systematic precision on both the model-independent and model-dependent determinations of the longitudinal polarization  $f_0$  by a factor of 1.3 compared to the best previous measurement [9] for a 1.4 times increase in luminosity, and are the most precise measurements to date.

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions.

This work was supported by the U.S. Department of Energy and National Science Foundation; the Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Culture, Sports, Science and Technology of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A.P. Sloan Foundation; the Bundesministerium für Bildung und Forschung, Germany; the World Class University Program, the National Research Foundation of Korea; the Science and Technology Facilities Council and the Royal Society, UK; the Institut National de Physique Nucleaire et Physique des Particules/CNRS; the Russian Foundation for Basic Research; the Ministerio de Ciencia e Innovación, and Programa Consolider-Ingenio 2010, Spain; the Slovak R&D Agency; and the Academy of Finland.

<sup>a</sup>Deceased.

<sup>b</sup>With visitors from University of Massachusetts Amherst, Amherst, MA 01003, USA.

<sup>c</sup>With visitors from Universiteit Antwerpen, B-2610 Antwerp, Belgium.

<sup>d</sup>With visitors from University of Bristol, Bristol BS8 1TL, United Kingdom.

<sup>e</sup>With visitors from Chinese Academy of Sciences, Beijing 100864, China.

<sup>f</sup>With visitors from Istituto Nazionale di Fisica Nucleare, Sezione di Cagliari, 09042 Monserrato (Cagliari), Italy.

<sup>g</sup>With visitors from University of California Irvine, Irvine, CA 92697, USA.

<sup>h</sup>With visitors from University of California Santa Cruz, Santa Cruz, CA 95064, USA.

<sup>i</sup>With visitors from Cornell University, Ithaca, NY 14853, USA.

<sup>j</sup>With visitors from University of Cyprus, Nicosia CY-1678, Cyprus.

<sup>k</sup>With visitors from University College Dublin, Dublin 4, Ireland.

<sup>l</sup>With visitors from University of Edinburgh, Edinburgh EH9 3JZ, United Kingdom.

<sup>m</sup>With visitors from University of Fukui, Fukui City, Fukui Prefecture, Japan 910-0017.

<sup>n</sup>With visitors from Kinki University, Higashi-Osaka City, Japan 577-8502.

<sup>o</sup>With visitors from Universidad Iberoamericana, Mexico D.F., Mexico.

<sup>p</sup>With visitors from University of Iowa, Iowa City, IA 52242, USA.

<sup>q</sup>With visitors from Kansas State University, Manhattan, KS 66506, USA.

<sup>r</sup>With visitors from Queen Mary, University of London, London, E1 4NS, United Kingdom.

<sup>s</sup>With visitors from University of Manchester, Manchester M13 9PL, United Kingdom.

<sup>t</sup>With visitors from Muons, Inc., Batavia, IL 60510, USA.

<sup>u</sup>With visitors from Nagasaki Institute of Applied Science, Nagasaki, Japan.

<sup>v</sup>With visitors from University of Notre Dame, Notre Dame, IN 46556, USA.

<sup>w</sup>With visitors from Obninsk State University, Obninsk, Russia.

<sup>x</sup>With visitors from University de Oviedo, E-33007 Oviedo, Spain.

<sup>y</sup>With visitors from Texas Tech University, Lubbock, TX 79609, USA.

<sup>z</sup>With visitors from IFIC(CSIC-Universitat de Valencia), 56071 Valencia, Spain.

<sup>aa</sup>With visitors from Universidad Tecnica Federico Santa Maria, 110v Valparaiso, Chile.

<sup>bb</sup>With visitors from University of Virginia, Charlottesville, VA 22906, USA.

<sup>cc</sup>With visitors from Bergische Universität Wuppertal, 42097 Wuppertal, Germany.

<sup>dd</sup>With visitors from Yarmouk University, Irbid 211-63, Jordan.

<sup>ee</sup>On leave from J. Stefan Institute, Ljubljana, Slovenia.

- [1] F. Abe *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **74**, 2626 (1995); S. Abachi *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **74**, 2632 (1995).
- [2] Charge-conjugate modes are included implicitly throughout this Letter.
- [3] C. Amsler *et al.* (Particle Data Group), *Phys. Lett. B* **667**, 1 (2008) and 2009 partial update for the 2010 edition.
- [4] J. Aguilar-Saavedra *et al.*, *Eur. Phys. J. C* **50**, 519 (2007).
- [5] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **99**, 151801 (2007).
- [6] M. Fischer *et al.*, *Phys. Rev. D* **63**, 031501(R) (2001); H. S. Do *et al.*, *Phys. Rev. D* **67**, 091501(R) (2003).
- [7] V. M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **102**, 092002 (2009).
- [8] V. M. Abazov *et al.* (D0 Collaboration), *Nature (London)* **429**, 638 (2004); V. M. Abazov *et al.* (D0 Collaboration), *Phys. Lett. B* **617**, 1 (2005).
- [9] T. Aaltonen *et al.* (CDF Collaboration), *Phys. Lett. B* **674**, 160 (2009).
- [10] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **98**, 072001 (2007); A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. D* **75**, 052001 (2007); A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. D* **73**, 111103 (2006); D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. D* **71**, 031101 (2005).
- [11] V. M. Abazov *et al.* (D0 Collaboration), *Phys. Rev. Lett.* **100**, 062004 (2008).
- [12] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **99**, 182002 (2007).
- [13] We use a cylindrical coordinate system where the  $z$  axis is along the proton beam direction and  $\theta$  is the polar angle. Pseudorapidity is  $\eta = -\ln \tan(\theta/2)$ , while transverse momentum is  $p_T = |p| \sin \theta$ , and transverse energy is  $E_T = E \sin \theta$ . Missing transverse energy,  $\cancel{E}_T$ , is defined as the magnitude of  $-\sum_i E_T^i \hat{n}_i$ , where  $\hat{n}_i$  is the unit vector in the

- azimuthal plane that points from the beam line to the  $i$ th calorimeter tower.
- [14] G. Mahlon and S. Parke, *Phys. Lett. B* **411**, 173 (1997); G. Mahlon and S. Parke, *Phys. Rev. D* **53**, 4886 (1996).
  - [15] F.A. Berends, W.T. Giele, and H. Kuijf, *Nucl. Phys. B* **321**, 39 (1989).
  - [16] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. D* **71**, 031101(R) (2005).
  - [17] A. Abulencia *et al.* (CDF Collaboration), *Phys. Rev. D* **74**, 072006 (2006); T. Aaltonen *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **100**, 211801 (2008).
  - [18] A. Bhatti *et al.*, *Nucl. Instrum. Methods Phys. Res., Sect. A* **566**, 375 (2006).
  - [19] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. D* **71**, 052003 (2005).
  - [20] D. Acosta *et al.* (CDF Collaboration), *Phys. Rev. Lett.* **97**, 082004 (2006).
  - [21] G. Corcella *et al.*, *J. High Energy Phys.* 01 (2001) 010.
  - [22] T. Sjostrand *et al.*, *Comput. Phys. Commun.* **135**, 238 (2001).
  - [23] M. Mangano *et al.*, *J. High Energy Phys.* 07 (2003) 001.
  - [24] J. Alwall *et al.*, *J. High Energy Phys.* 09 (2007) 028.
  - [25] G.J. Feldman and R.D. Cousins, *Phys. Rev. D* **57**, 3873 (1998).